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A Multiscale Review of Contemporary Climate Models

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A MULTISCALE REVIEW OF CONTEMPORARY CLIMATE MODELS

by

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A Research Paper
Submitted in Partial Fulfillment of the Requirements for the
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RESEARCH APPROVAL

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ABSTRACT

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TITLE: A MULTISCALE REVIEW OF CONTEMPORARY CLIMATE MODELS

MAJOR PROFESSOR: Dr. Justin Schoof

Atmospheric Oceanic General Circulation Models (AOGCMs) are the primary tools that climate scientists use to investigate past, present and potential future climate. This research paper provides an overview of the strengths and weaknesses of contemporary models across spatial and temporal scales. At large spatial scales, models simulate recognizable patterns of the major modes of climate variability, with a few caveats. Deficiency in reproducing the strength of individual centers of action and detailed temporal characteristics has been noted. The models that best reproduce the spatial pattern are not necessarily the models that simulate the most realistic temporal pattern. Models generally capture observed synoptic scale regimes well, but studies have noted differences in observed and simulated frequencies of specific synoptic patterns as well as differences in seasonality, which could be associated with the links between hemispheric scale climate and synoptic scale circulation. At the regional scale, little literature exists to identify the minimum scale at which GCMs correspond well with observed statistical moments, especially for large ensembles and variables other than temperature and precipitation. Recognition in the climate science community that model performance at small scales is dependent on reliable simulation of processes occurring across scales has led to a new focus on multi-scale assessment of AOGCM fidelity.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. Introduction

The global mean near-surface air temperature has increased by approximately 0.75°C in the last century (Trenberth et al. 2007), raising concerns about potential climate change impacts, including sea level rise (Church et al. 2001, Lemke et al. 2007, Bindoff et al. 2007) and subsequent effects on coastal infrastructures (Nicholls et al. 2007, Day 2004, Pilkey and Cooper 2004), changes in the frequency and intensity of heat waves and tropical cyclones (Meehl et al. 2007) and floods and droughts (Kundzewicz et al. 2007, Rosenzweig et al. 2007), effects on the ecosystem goods and services (Schneider et al. 2007) and alteration of the geographical extent of vector borne diseases (Confalonieri et al 2007) among others. Atmospheric Oceanic General Circulation Models (AOGCMs), coupled mathematical models that numerically represent physical, biological and chemical processes that govern climate, are the principal investigative tools (Gates et al. 1990) used to assess the historical behavior of climate system (e.g. Jansen et al. 2007); analyze current climate system behavior (e.g. Randall et al. 2007, Hegerl et al. 2007) and make projections about future climatic conditions (e.g. Cubasch et al. 2001; Meehl et al. 2007). It is therefore critical that the strengths and weaknesses of AOGCMs are explicitly quantified over the range of spatial and temporal scales that are typically used. Earth System Models (ESMs), that include biogeochemical cycles and their interactions with the climate system and human actions, are very important where biogeochemical feedback plays an important role in past simulation and future projections but for this paper a comprehensive performance of AOGCMs at various scales has been emphasized.

Policy makers, planners, engineers and impact modelers need information at finer spatial and temporal scale than AOGCMs are currently able to provide (Schoof et al. 2009, Maruan et al. 2010). Use of AOGCMs to investigate climate change impacts assumes that they adequately simulate climate across a range of spatial and temporal scales. While the shortcomings of AOGCMs at the scale of an individual grid point have been recognized within the AOGCM downscaling community, there has been paucity of literature that identifies the scale at which AOGCMs perform well, especially for variables other than temperature, and for large model ensembles.

Phase 5 of the Coupled Model Intercomparison Project or CMIP5 (Taylor et al. 2012) is an initiative of World Climate Research Programme's (WCRP) Working Group on Coupled Modeling (WGCM) and successor of CMIP3. CMIP5 presents an extensive experimental design through which more than 20 modeling groups present model output for historical, present and future periods using more than 50 models (Meehl and Bony 2011, Taylor et al. 2012). This provides the foundation of 5th Assessment report (AR5) of the Intergovernmental Panel on Climate Change (Stouffer et al. 2011).

AOGCMs are relatively more skillful in simulating average climate at continental scales across seasons but they are not as reliable when approaching smaller spatial and temporal scales. The assessment of relative ability of AOGCMs to simulate large scale modes of climate variability is important to determine how the models perform at the large spatial and temporal scales where the model simulations are considered robust. Review of model performance at synoptic scale is another important model diagnostic as it indicates the ability of the models to simulate the synoptic scale features such as storms and jet streams which have implications for large scale events.

Successful reproduction of synoptic features will increase our confidence in model simulation at large scale. Model simulation at the smaller spatial and temporal scale is the most critical aspect of model performance as uncertainty in model simulation increases as we move from a global scale to a regional scale and from seasonal scale to daily time scale. Models that are more successful at large scale and synoptic scale are more likely to simulate the small scale features as the large scale and synoptic scale events influence regional climate.

The goal of this review is to assess the performance of the state of the art AOGCMs across a range of spatial and temporal scales to evaluate their strengths and weaknesses for application in climate change impact studies. However, an assessment of every specific feature of each model is beyond the scope of this paper but review of strength and weaknesses of contemporary climate models is the focus of this paper. Towards that goal, performance of AOGCMs is evaluated across 3 clearly defined scales. These are 1) Large continental scale – scale at which large scale modes of climate variability are adequately resolved, 2) Synoptic scale – scale at which daily variability of jet streams and the intensity of semi-permanent pressure systems and storm tracks are adequately captured. 3) Regional or local scale – scale at which regionally averaged climate information is still relevant for regional impact assessment studies. Climate scientists have used larger sub continental scales such as 1000 km *1000 km (Christensen et al. 2007), 10^6-10^8 km^2 (Ruosteenoja et al. 2003) and 10^7 km^2 (Giorgi and Francisco 2000) for regional applications. The review is divided into 3 distinct parts discussing the 3 above mentioned scales in section 2, 3 and 4 respectively.

At the largest spatial scales, there are fundamental modes of variability that describe much of the annual and interannual variability in large scale climate (Schoof and Pryor 2006, Coleman and Klink 2009). Synoptic scale circulation is strongly influenced by the large-scale modes. An evaluation of AOGCMs at the synoptic scale will be an important aspect of model evaluation since synoptic scale links the large scale climate and regional or small scale climate. From the perspective of climate modeling, the synoptic scale is a horizontal length scale at which low pressure areas and high pressure areas of the lower troposphere are adequately resolved. Orlanski (1975) has described that the Mesoscale-α (200-2000 km) is the scale at which front, low pressure systems and hurricanes are formed and the upper limit of mesoscale-α borders on the lower limit of synoptic scale. In the extra-tropics, the synoptic scale circulation is a controlling influence on the climate at the regional and local scale (Hewitson and Crane 1992). If a model is unable to perform well at large scale and synoptic scale then the regional simulation of the model is also likely to lack fidelity. For a regional impact study it is important to capture most of the features regulating climate in that particular region and coarse resolution AOGCM output at grid point level is not very effective in this regard. It is thus important to determine the skill of AOGCM simulation at the regional scale where they can still produce locally relevant climate information.

2. Model simulation of Large-scale Climate Variability

2.1 Introduction

Teleconnections are recurring and persistent large scale events that vary on a large spatial and temporal scale. Mode of variability can be broadly defined as the statistical relationship among climatic variables that forms a link between two distant points of the global climate system by establishing a relationship between large scale oceanic and atmospheric dynamics and regional climatic features (Leathers et al. 1991). These patterns are recognized by measuring anomalies in sea level pressure (SLP), sea surface temperature (SST) or geopotential height fields (Stoner et al. 2009).

The objective of this section is to review the capability of the state of the art AOGCMs in simulating the major modes of variability. The major emphasis is on the evaluation of the modes of variability influencing the climate of Northern Hemisphere while also assessing some of the major modes of variability in the Southern Hemisphere. Towards that goal, six major modes of variability are evaluated: the Arctic Oscillation (AO), the North Atlantic Oscillation (NAO), the Pacific North American pattern (PNA), the Atlantic Multidecadal Oscillation (AMO), El Nino-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO).

a) <u>Arctic Oscillation (AO)</u>

The Arctic Oscillation has been defined as the leading empirical orthogonal function of monthly SLP anomaly during winter from 20° N towards the Arctic pole (Thompson and Wallace 1998; Thompson et al. 2000; Thompson and Wallace 2000). The Arctic Oscillation (AO) accounts for 22% of the total variance as the first principal component of the average monthly Sea Level Pressure (SLP) anomaly during winter for the region between 20°N and 90°N (Thompson and Wallace 1998). Trenberth and Paolino (1981) reported that 28.5 % of the variance of monthly winter SLP anomaly and 20.3% of annual SLP anomaly for the region north of 20°N could be explained by the first EOF pattern.

Lower than normal sea level pressure in the Arctic region and higher than normal pressure in the middle latitudes are experienced during the positive phase of AO (Figure 1a). As a result, strong westerly winds keep the cold arctic air confined to the polar region. The positive phase of AO makes both northern Europe and most of the U.S. experience warmer and wetter winters.

b) <u>North Atlantic Oscillation (NAO)</u>

Walker (1923) identified the presence of a pressure anomaly “between the Azores and Iceland, and between the areas of high and low pressure in the N. Pacific”. Walker (1924) reported this seesaw in pressure anomaly as North Atlantic Oscillation (NAO). The NAO has nodes and anti nodes located in Iceland and Azores-Bermuda. The pressure center between Greenland and Iceland is known as Icelandic low and the one in North Atlantic is known as Azores high (Figure 1b). The North Atlantic Oscillation (NAO) is responsible for 31% of Northern Hemispheric surface temperature variation during winter (Hurrell 1996). The focus of the second section is on reviewing the performance of AOGCMs in simulating the modes of variability.

Positive NAO produces stronger than average Icelandic low and Azores high, forming a stronger than average pressure gradient in the north Atlantic that gives rise to stronger westerlies. Negative NAO indicates a weaker than normal Icelandic low and Azores high that produces weaker westerlies. Barnston and Livezey (1987) reported NAO as the strongest pattern of both summer and winter Northern Hemispheric circulation. During positive NAO, stronger pressure gradient increases the frequency and intensity of storm events across the Atlantic during winter. As a result, warmer and wetter winter is experienced in Europe while the Northern part of Canada and

Greenland experience a colder and drier winter and Eastern US gets a wetter and warmer winter.

c) <u>Atlantic Multidecadal Oscillation (AMO)</u>

Atlantic Multidecadal Oscillation (AMO) is a natural mode of variability that is principally identified through the sea surface temperature anomalies in North Atlantic Ocean. AMO has a cycle of 65-70 years (e.g. Schlesinger and Ramankutty 1994, Stoner et al. 2009). Bjerknes (1964) was seminal in identifying the change in atmospheric thermodynamics due to warm sea surface temperature (SST) anomaly in the North Atlantic and attributing it to atmospheric circulation patterns. During the warm phase of AMO, lower than normal precipitation is experienced in most of the U.S. (Enfield et al. 2001). Positive AMO phase produces a horseshoe shaped pattern of sea surface temperature anomalies in the North Atlantic region with a prominent warming in the tropical and some regions of eastern subtropical North Atlantic (Figure 1c). This also causes the southernmost regions of Greenland to experience warming and regions off the east coast of the US experience cooling (Bjerknes 1964, Kushnir 1994, Grossmann and Klotzbach 2009).

d) <u>The El Niño–Southern Oscillation (ENSO)</u>

Walker (1923) first described the presence of a large scale pressure anomaly between the regions close to Pacific and Indian Ocean. Walker (1924) named this oscillatory mode of variability as the southern oscillation, which caused increase in pressure at regions close to Pacific that included San Francisco, Tokio, Honolulu, Samoa and South America and decrease in pressure at locations close to the Indian Ocean that included Cairo, Northwest India, Port Darwin, Mauritius, and south east

Australia. Bjerknes (1966) found that the warm SST anomaly in the central and eastern equatorial Pacific during the winter period between November 1957 and February 1958 was running concurrent with an anomalous strengthening of westerlies or anti-trades over the northeast Pacific. Bjerknes (1969) found that the presence of strong westerlies accompanied by increased SST anomaly in the equatorial Pacific that was observed during the winter period ranging from November 1957 to February 1958 was recurrent in the winters of 1963-1964 and 1965-1966. He concluded that El Niño and the southern oscillation are associated and are different facets of a single mechanism.

The warm or positive phase of ENSO, El Niño, causes drier and warmer winter in the Northwest, northern Midwest and northern Mideast United States that results in a decreased snowfall in these areas during winter and a wetter winter is experienced by northwest Mexico and southwest United States that includes central and southern California. El Niño produces a cooler and wetter winter in northeast Mexico and southeast United States. El Niño is associated with warm SST anomaly in the central and eastern equatorial Pacific (Figure 1d) for several months during the Christmas that has an average cycle of 2-7 years (Bridgman et al. 2006).

Under neutral conditions or La Nada conditions, strong easterlies or trade winds blowing from east to west in the equatorial Pacific causes the displacement of warm water from the west Pacific to eastern Pacific. As a result colder deeper water rises to replace the displaced warm water in the eastern Pacific. This is marked by warm water conditions in the western Pacific and cold water condition in the eastern Pacific. El Niño triggers a strengthening of westerlies which drives back some of the warm water from the western Pacific to eastern Pacific and this also prevents the upwelling of cold water in the eastern Pacific. This causes the warm SST anomaly in the eastern Pacific (Aguardo and Burt 2012).

The negative (cool) phase of ENSO, La Niña, produces the opposite effect of El Niño. La Niña represents the strengthening of the normal cold water conditions in the eastern equatorial Pacific accompanied by warm water conditions in the western tropical Pacific (Aguado and Burt 2012).

e) <u>Pacific Decadal Oscillation (PDO)</u>

PDO is defined as one of the leading modes of variability in extratropical north Pacific with an average period of 2-3 decades and is recognized by measuring SST anomaly (Mantua et al. 1997, Nigam et al. 1999, Minobe 2000, Mantua and Hare 2002, MacDonald and Case 2005). A positive or warm phase of PDO (Figure 1e) produces a reduction in rainfall, snowpack and streamflow during winter in the northwest U.S. and increases precipitation in the southwest United States, Mexico, coastal Gulf of Alaska, southeast Brazil, Western Australia and the central part of South America. It also causes drier conditions in eastern Australia, Korea, Japan, the outermost regions of East Russia, Zonal regions from the Pacific Northwest to the Great Lakes, the Ohio Valley, most of Central America as well as Northern South America (Mantua and Hare 2002). Power et al. (1998, 1999) described this multidecadal mode of variability as Interdecadal Pacific Oscillation (IPO).

Climatic anomalies related with PDO are very similar to that of mild El Niño and La Niña events (Latif and Barnett 1996, Mantua et al. 1997, Minobe 1997, Mantua and Hare 2002). Zhnag et al. (1997) described this multidecadal oscillation as “ENSO-like EOF mode in the global SST field”. Mantua et al. (1997) stated that both ENSO and

PDO have spatial and temporal patterns that are related and PDO could be described as “ENSO-like interdecadal climate variability”, which is similar to the findings of Tanimoto et al. (1993) and Zhang et al. (1997).

f) <u>Pacific North American pattern (PNA)</u>

Pacific North American pattern is a distinct mode of variability, at middle and upper tropospheric level with geopotential height anomaly over the North Pacific Ocean and North America and very prominent during winter, was first identified by Wallace and Gutzler (1981). Shukla and Wallace (1983), Blackmon et al. (1983) used GCMs to investigate the response of atmospheric circulation to SST anomaly and were able to simulate PNA over equatorial Pacific during Northern Hemispheric winter. Tokioka et al. (1985) in a similar study was able to simulate PNA for the period between May to June using a GCM.

Leathers et al. (1991) examined monthly variation of PNA with temperature and precipitation, from 1947-1982 during autumn, spring and winter when PNA is considered to be a major mode of variability in Northern Hemisphere and reported significant relationship between temperature in most of the United States and PNA. For temperature, areas of strong positive and negative correlation were found in northwest and southeast US respectively. During winter, greater than 80% of temperature variation ($R > 0.9$) was explained by PNA for some of the areas within the stated regions and was significant during spring and autumn. A significant relationship between United States precipitation and PNA was reported with the exception of April, May, September and October. The relationship for precipitation is somewhat weak and lesser in magnitude compared to temperature but strong correlations were found in

Upper Mississipi and Northern Rockies in January, Ohio Valley in February, Ohio Valley and some regions of southern Great Plains in March, Upper Mississippi valley and large part of western U.S. in November, Mississippi valley and western U.S. in December.

Leathers and Palecki (1992) also associated the 1957-1987 positive PNA values with lower atmospheric temperature during winter over US. This is supported by Yin (1996), Cronin et al. (2002), Schoof and Pryor (2006). Henderson and Robinson (1994) found significant correlation between PNA pattern and precipitation in some parts of southeastern US with Negative PNA producing drier winter and wetter summer. Henderson and Vega (1996) also found significant positive correlation between PNA index and precipitation events during summer in southeast United States. Henderson and Vega (1996) found 28.2% variation in winter precipitation of Florida was influenced by PNA. The positive PNA is responsible for increase in atmospheric instability, development of thunderstorms and wetter winter in southeastern U.S. (Cronin et al. 2002). Positive PNA (Figure 1f) gives rise to an extended ridge in northwest U.S. and a deep trough over southeast US and Aleutian island (Wallace and Gutzler 1981, Slowey and Crowley 1995, Sheridan 2003). This results in meridional flow over US, whereas negative PNA index is associated with more zonal flow. Slowey and Crowley (1995) has discussed the relationship between lower SST and positive values of PNA in southeast United States.

Barnston and Livejey (1987) reported the absence of PNA as a major mode during the Northern Hemispheric summer circulation but found it present from September through April with the exception of November and attainment of maximum strength in February. The average period for PNA is from of 1-4 years (Stoner et al. 2009).

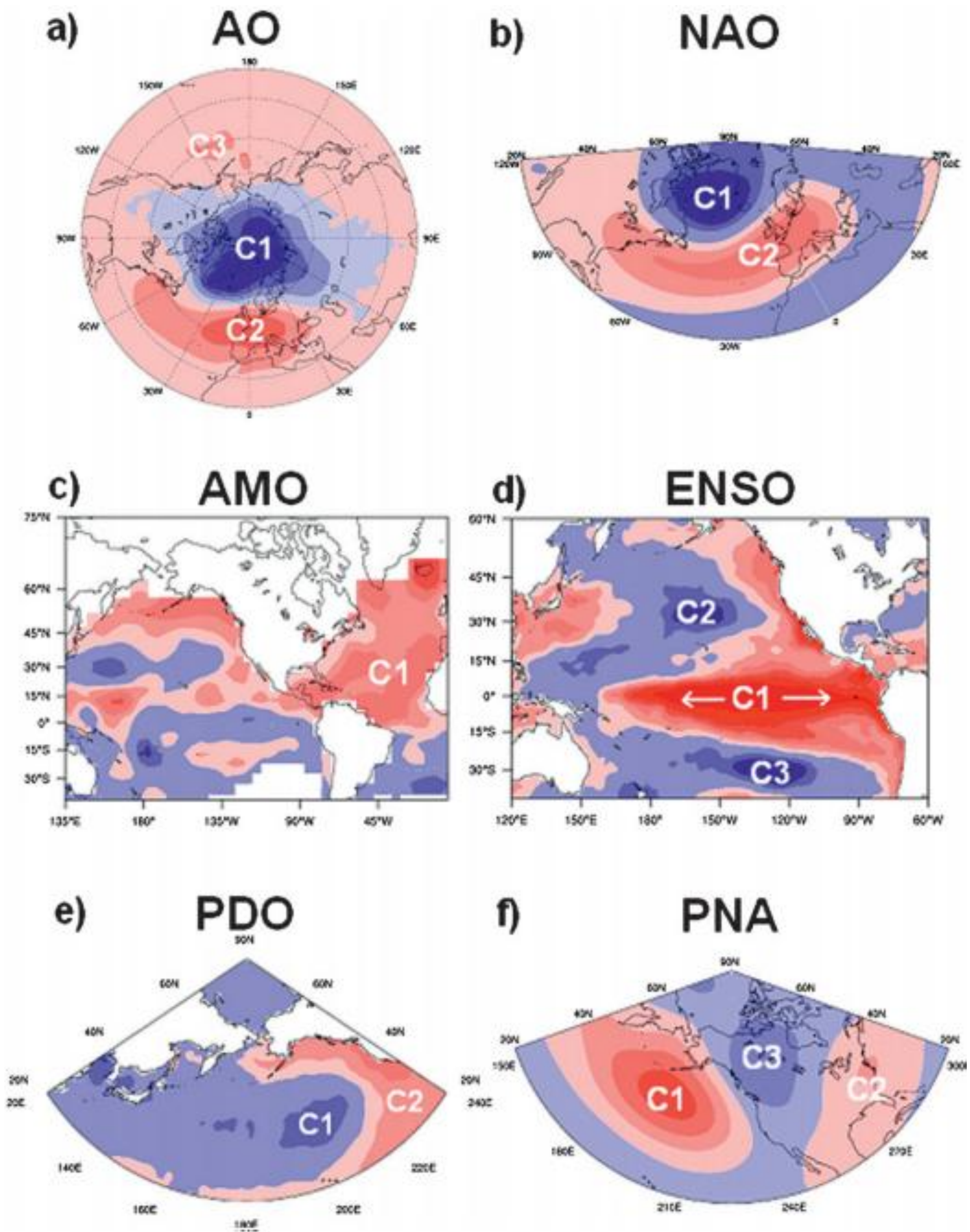

Figure 1. Spatial pattern of a) the AO calculated from monthly 950 hPa geopotential height field b) the NAO calculated from monthly 500 hPa geopotential height fields c) the AMO calculated from monthly SST anomaly d) the ENSO calculated from monthly SST anomaly e) PDO calculated from monthly SST anomaly and f) PNA calculated from monthly 500 hPa geopotential height fields. (Figure reproduced from Stoner et al. 2009). ©American Meteorological Society. Used with permission.

2.2 Assessment of Model Performance at Large Scale

Stoner et al. (2009) reviewed the ability of the CMIP3 AOGCMs to simulate the spatial and temporal patterns of specific teleconnection events and found that both coupled and uncoupled AOGCMs replicate the AO, ENSO, NAO and PNA patterns well in general. However, there were intermodal differences and systematic biases when compared with observed spatial and temporal patterns.

Xiao-Ge et al. (2008) evaluated the ability of 23 CMIP3 AOGCMs in simulating Northern Hemispheric winter and stated all models except one simulated AO as the principal empirical orthogonal function of extratropical SLP anomaly during Northern Hemispheric winter. Stoner et al. (2009) in a similar study used 22 CMIP3 AOGCMs and found that most of the models were able to reproduce a spatial and temporal pattern that is similar to the observed AO pattern. Hurrell et al. (2006) used CAM3, the atmospheric component of coupled AOGCM CCSM3, to simulate the Northern Annular Mode (NAM) or AO and found that model simulation produces a pattern that is identical with observed NAM/AO. Miller et al. (2006) used 14 CMIP3 models and reported that the simulated NAM/AO and the observed pattern of NAM/AO show high spatial correlation. Gerber et al. (2008) evaluated the ability of CMIP3 models in simulating the temporal pattern of NAM and found that the models broadly replicate the general temporal patterns but also found intermodal differences arising from systematic biases in simulating the temporal pattern. The problem was more severe for the Southern Hemispheric counterpart of NAM where the time scales were unusually longer compared to Northern Hemisphere and multimodel ensemble average was two times higher than observed reanalysis data.

Handorf and Dethloff (2012) evaluated the ability of a suite of 23 CMIP3 AOGCMs in reproducing the spatial and temporal characteristics of NAO and PNA along with some other teleconnections in Atlantic and Pacific. They found that although the spatial and temporal patterns of atmospheric teleconnections were simulated well by most of the GCMs but there was scope of improvement for the models in simulating the strength of centers of action for the teleconnections. In general, the pacific patterns were reproduced better than the Atlantic patterns with some models performing poorly in both the regions. They observed model deficiency in simulating the spatial and temporal pattern over the shorter time scale and concluded the overestimation in the persistence of the teleconnections on the sub seasonal and seasonal time scale was responsible for reproducing the deviation from annular mode time scale observed in reanalysis data. It has been noted that most GCMs tend to produce too strong an annular structure for NAO than observed (McHugh and Rogers 2005; Xiao-Ge et al. 2008; Stoner et al. 2009; Flato et al. 2013). An attempt to project future European temperature analysis done with 33 CMIP5 models by Cattiaux et al. (2013) revealed that majority of CMIP5 models tend to project increase in the frequency of negative NAO in future which is contrary to the projection of increase in the frequency of positive NAO by CMIP3 models.

AchutaRao and Sperber (2002) used 17 CMIP2 AOGCMs and found most of them were unable to simulate the sea level pressure variation caused by ENSO in the eastern Pacific resulting in erroneous precipitation response. CMIP2 models overestimated the frequency of ENSO events. However, CMIP3 models were much more efficient at simulating the frequency of ENSO (AchutaRao and Sperber 2006).

Single model simulation of ENSO attempted by Min et al. (2005) indicated an overestimation of frequency and intensity of ENSO by ECHO-G model. However, Cai et al. (2003) found that CSIRO mark 3 GCM produced realistically similar spatial pattern and frequency when compared with historical ENSO records. Van Oldenborgh et al. (2005) found mixed results with the CMIP3 model ensemble where 6 models overestimated the frequency of ENSO cycles but 4 models were able to match the observed spatial and temporal pattern of ENSO. Models often simulate an ENSO pattern that expands too far into the western equatorial Pacific (Cai et al. 2003; Min et al. 2005; van Oldenborgh et al. 2005; AchutaRao and Sperber 2006; Reichler and Kim 2008; Guilyardi et al. 2009). The CMIP3 models were relatively successful at reproducing the general mean state and annual cycle of ENSO (Randall et al. 2007). Most CMIP3 models did not reproduce the observed ENSO variability at the 2-7 year time scale but most of the CMIP5 models do capture the observed spectral peak for ENSO at the 2-7 year time scale. Models still show errors in reproducing the amplitude, period, irregularity, skewness and spatial pattern due to little seasonal modulation or phase locking that does not reflect the observed El Niño and La Niña anomalies strongest in the Northern Hemispheric winter (DJF) and weakest in the Northern Hemispheric spring (MAM) with few exceptions (Guilyardi et al. 2009). The intermodal spread for the simulation of amplitude of El Niño is much smaller in CMIP5 compared to CMIP3 models (Kim and Yu 2012; Flato et al. 2013). Models continue to have the well-known double ITCZ problem resulting in an erroneous reproduction of ITCZ in the Southern Hemisphere causing excessive precipitation over the tropics (Mechoso et al. 1995; Lin 2007). This remains a major source of model error in simulating the annual cycle in the tropics and can affect the reliability of ENSO simulations (Guilyardi et al. 2003, 2009; Sun et al. 2009). Kim and Yu (2012) noted that compared to CMIP3 models, observed spatial patterns were better reproduced by CMIP5 models, although models continue to have difficulty in reproducing the realistically strong observed EP (Eastern Pacific) ENSO intensity compared to strong observed CP (Central Pacific) ENSO intensity. A comparative study between 21 CMIP3 and 31 CMIP5 models by Gao et al. (2015) showed that both the 31 model and the best 8 model ensemble from CMIP5 outperformed corresponding CMIP3 model ensembles in reproducing the dominant mode of summer precipitation in the Pan-Asian monsoon region as the CMIP5 models better represented the ENSO pattern as well as the relationship between Antarctic Oscillation in the south Pacific Ocean and ENSO which represented the dominant mode in summer precipitation indicating improved air-sea interaction of Southern Hemisphere in CMIP5 models.

Sheffield et al. (2013) used 27 CMIP5 models to examine AMO, PDO and ENSO simulations and teleconnections with North American climate and found that frequency and mean state of ENSO are well represented but only few models could reproduce the CP ENSO, EP ENSO and the teleconnections with the North American winter time temperature. Model efficiency in simulating certain aspects such as the two types of ENSO and the observed teleconnection also did not mean efficiency in simulating other features such as ENSO asymmetry. Spatial pattern for PDO and teleconnection with temperature and precipitation was reasonably reproduced with less efficiency in winter. AMO spatial patterns showed improvements over CMIP3 results and particularly after 1960 but SST seasonality was not captured well with larger strength in summer and discrepancy in spatial structure as maximum SST anomalies were reproduced over the mid-Atlantic Ocean instead of the observed maximum over the south of Greenland. Sheffield et al. (2013) concluded that CMIP5 models have not shown a great deal of improvements over CMIP3 models in this regard. Langenbrunner and Neelin (2013) investigated the ENSO precipitation teleconnections for the Niño 3.4 region and found very little improvement in CMIP5 ensemble with that of CMIP3 in reproducing the amplitude and spatial pattern for ENSO precipitation teleconnection in that region.

Schoof and Pryor (2006) evaluated the ability of CMIP3 coupled AOGCMs HadCM3 and CGCM2 to reproduce the NAO and PNA and found both GCMs were relatively good at reproducing the 500 hPa pressure pattern. However, significant intermodal differences were found. In a sequel paper, Schoof and Pryor (2014) employed 10 CMIP5 AOGCMs and found good correspondence between the observed AO, PNA and ENSO spatial pattern with the simulated spatial pattern, although the match was better for AO and PNA compared to ENSO. The results indicate that CMIP5 models overestimated the magnitude and the spatial extent of the node in the polar region whereas Stoner et al (2009) found that CMIP3 models underestimate the magnitude of the center of action at the high latitude (C1 region in figure 1a). For PNA, considerable intermodal difference was found in estimating the magnitude of the center of actions. The observed seasonal timing for ENSO, that features anomalies peaking in Northern Hemispheric winter and falling at the Northern Hemispheric spring, is also not captured by CMIP5 AOGCMs which is consistent with the findings of Guilyardi et al. (2009) and Sheffield et al. (2013). In reproducing the temporal pattern for AO, ENSO and PNA, models that failed to capture the seasonal pattern well were found to be good at simulating the temporal pattern and at times models that performed poorly in simulating the spatial pattern simulated the temporal pattern well. This is in agreement with the findings of Stoner et al. (2009) that found CMIP3 models that produce best temporal patterns are not essentially the models with best spatial patterns which shows the importance of including all the models in analyzing the spatial and temporal pattern as no single model was found to outperform the other models in CMIP5 consistent with CMIP3 model performances.

2.3 Summary

Climate models have made great improvements in the past two decades and as they continue to improve, a review of model performance to analyze their strengths and weaknesses across various spatial and temporal scales is required. At the large spatial scale, where the model simulations are considered robust, a general improvement has been noted in CMIP5 models compared to their CMIP3 counterparts and this has been attributed to the presence of lesser number of poorly performing models in the CMIP5 suite of models (Flato et al. 2013). In general, CMIP5 models simulate a recognizable spatial and temporal pattern for the modes of climate variability discussed in this section but as was the case for CMIP3 models, a varied spectrum of model performance is also witnessed for CMIP5 models. Kim and Yu (2012) found that the CMIP5 models reproduce the observed EP ENSO and CP ENSO spatial patterns better and show less inter-model spread compared to CMIP3 models. Gao et al. (2015) reported that CMIP5 models are more skillful in reproducing the primary mode of summer precipitation in Pan-Asian monsoon region. Langenbrunner and Neelin (2013) found that the ability of the CMIP5 models in reproducing the amplitude and spatial pattern for ENSO precipitation teleconnections has not shown great improvement compared to CMIP3 models. Modes of variability with multidecadal variance such as AMO and PDO present stronger challenge as the observational period is too short and remain less investigated than the others. Among AO, NAO, PNA and ENSO, the models continue to have significant challenges and more so in simulating ENSO. CMIP5 models still show error in reproducing the observed ENSO amplitude period, irregularity, skewness although the mean state and seasonal cycle is well represented in both CMIP3 and CMIP5 models (Flato et al. 2013). CMIP5 models also continue to have deficiency in simulating the realistically strong EP ENSO and CP ENSO intensity and more so for EP ENSO but CMIP5 models show less intermodal spread which represents better consistency of model performance compared to CMIP3 models (Kim and Yu 2012, Flato et al. 2013). Most of the CMIP5 models are able to reproduce the observed ENSO 2-7 year peak in the power spectra which was a noted deficiency in most of the CMIP3 models. Although CMIP5 models are claimed to have lesser number of poorly performing models, there is scope for improvement in individual model performance in simulating the strength of center of action for the modes of interannual and interdecadal variability. Similar to the findings of Stoner et al (2009) for CMIP3 models, it has been reported that CMIP5 models that are good at simulating the spatial pattern are not always the models that reproduce the best temporal pattern (Schoof and Pryor 2014). This presents an important aspect of model simulation which calls for an analysis of contemporary climate models to determine if some models produce better match with the observed historical simulation in a specific study area and should be included in the analysis for that specific region. Table-1 provides a summary of major findings of model performance at large scale.

Table-1: A Summary of Model Performance at Large Scale

Primary reference	Dataset(s)	Model(s) used	Data type	Major findings
Gerber et al. (2008)	NCEP/NCAR reanalysis (NNR) for observed zonal wind data	17 CMIP3 GCMs	Daily	Models broadly simulate the observed time scale of NAM and SAM. However, systematic overestimation of the time scales for SAM in the Southern Hemispheric summer and spring is noted with broader annual cycles in both the hemispheres.
Schoof and Pryor (2006)	NNR for observed sea level pressure and geopotential height data.	2 CMIP2 GCMs	Daily	A high degree of correspondence between simulated and observed temporal behavior of NAO and PNA is reported but intermodal differences are noted.
Stoner et al. (2009)	ERA-40, NNR and Kaplan SST V2 for observed geopotential height and sea surface temperature (SST)	22 CMIP3 models	6 hourly and monthly	Models reproduce a spatial pattern that closely matches with the observed spatial pattern of all 6 modes of variability with limited success for AMO. Most models show a recognizable temporal pattern but models that show the best spatial pattern are not necessarily the models with the best temporal pattern. Also, overestimation or underestimation of strength of spatial pattern is noted and models often show temporal variability that is a) too slow or too rapid and b) too regular compared to the observed.
Handorf and Dethloff (2012)	ERA-40 and NNR for observed geopotential height data	23 CMIP3 models	Monthly	Spatial Pattern of NAO, PNA and some other modes of variability show good correspondence with observed spatial pattern but intermodal differences in simulating the strength of centers of action is noted. Models display a temporal pattern somewhat similar with the observed temporal pattern but the range of observed temporal characteristics are not captured which is consistent with the findings of Stoner et al. (2009).

Table-1: Continued

Primary reference	Dataset(s)	Model(s) used	Data type	Major findings
Kim and Yu (2012)	The Extended Reconstruction of Historical Sea Surface Temperature version 3 (ERSST V3) for observed SST	20 CMIP5 and 19 CMIP3 models	Monthly	Compared to CMIP3 models, observed spatial pattern for ENSO is better reproduced by CMIP5 models. The intermodal spread in simulating the ENSO intensities is much smaller in CMIP5 suite of models although the models continue to have difficulty in simulating realistically strong Eastern Pacific (EP) ENSO intensity compared to strong observed Central Pacific (CP) ENSO intensity.
Flato et al. (2013)	NA	NA	NA	CMIP5 models still show error in reproducing the observed ENSO amplitude, period, irregularity and skewness although the mean state and seasonal cycle are well represented in both CMIP3 and CMIP5 models.
Sheffield et al. (2013)	NNR, NCEP-DOE, ERA-Interim, 20 CR, TMPA 3B 42 V6, CRU TS3.1, CPC-Unified, GPCP v2.1, UNAM v0705, CRU TS3.1, HadISST, ERSST.v3b for observed temperature, precipitation and SST	27 CMIP5 models	3-hourly, 6-hourly, daily, monthly	CMIP5 models have not shown improvements in capturing the seasonal timing of ENSO peaking in fall and winter. Frequency and mean state ENSO are well represented but only a few models are able to display the EP and CP ENSO and teleconnections with North American winter. The spatial representation of AMO and PDO is reasonable. However, PDO teleconnections with temperature and precipitation was less efficient in winter.
Langenbrunner and Neelin (2013)	Extended Reconstructed Sea Surface Temperature (ERSST) version 3 for observed SST, CMAP for observed precipitation	15 CMIP5 models and 13 CMIP3 models	Monthly	CMIP5 models show little improvement in reproducing the amplitude and spatial pattern of ENSO precipitation teleconnections in the region of strong observed teleconnection.

Table-1: Continued

Primary reference	Dataset(s)	Model(s) used	Data type	Major findings
Schoof and Pryor (2014)	NNR for observed SST, sea level pressure and wind speed	10 CMIP5 models	Daily	CMIP5 models show general agreement between the simulated and observed AO, PNA and ENSO pattern, although the match was better for AO and PNA compared to ENSO. Models that capture the spatial pattern well are not necessarily the models that simulate the temporal pattern well which are consistent with the findings of Stoner et al. (2009).
Gao et al. (2015)	NNR and GPCP for observed precipitation and Hadley Center Sea surface Temperature data for observed SST	21 CMIP3 and 31 CMIP5 models	Monthly	CMIP5 models outperformed CMIP3 models in reproducing the dominant mode of summer precipitation in the Pan-Asian monsoon region due to more realistic simulation of ENSO in the central-eastern equatorial Pacific.

3. Model Simulation of Synoptic Scale Features

3.1 Introduction

Schoof and Pryor (2006, 2009) found that the frequency of several synoptic map patterns occurring in the Midwestern region of the US were dependent on the positive or negative phase of a single mode of variability (NAO or Pacific North American Pattern i.e. PNA) and sometimes on the phase of more than one modes of variability (NAO and PNA). The climate of much of the United States is prone to high daily variability due to relative changes in the intensity of the polar jet streams and semi-permanent pressure systems that include subtropical high and subpolar low. Change in the intensity of these low and high pressure systems are reflected through the modes of variability which in turn inflict change on the intensity and frequency of synoptic scale events which finally manifest in local or regional scale events (Schoof and Pryor 2009). The focus of the third section is on the evaluation of synoptic scale circulation by AOGCMs.

Li et al (2011) analyzed the impact of changes in the North Atlantic subtropical high (NASH) on summer precipitation of southeast United States by applying CMIP3 model simulations and reported a westward displacement of NASH in future which is likely to cause increased extreme occurrences of dry and wet summers in southeast United States. From the perspective of synoptic climatology, the links between atmospheric circulation and regional scale climate is analyzed by applying widely accepted classification techniques such as weather classification, air mass classification and circulation types that categorize the atmospheric conditions into different groups that as a whole is representative of all pertinent atmospheric states (Yarnal 1993, Huth et al. 2008, Sheridan and Lee 2012). Synoptic scale simulation holds an important link between large scale modes and regional scale climate and the effect of large scale features on regional climate can be assessed by examining the variation in atmospheric circulation with regard to changes in the modes of variability (Sheridan and Lee 2012).

A general overview of classification of synoptic circulation is described in Yarnal (1993), Yarnal et al. (2001) and Huth et al. (2008). A wide variety of approaches for the classification of circulation pattern have been applied to various GCM application studies. Employment of the Lamb synoptic classification (Tolika et al. 2006; Anagnostopoulou et al. 2008, 2009; Demuzere et al. 2009), Self organizing maps (e.g. Cassano et al. 2006, 2007; Lynch et al. 2006; Finnis et al. 2009a, 2009b), Kirchhofer correlation based classification (Crane and Barry 1988; McKendry et al. 1995; Saunders and Byrne 1996; Schoof and Pryor 2006), mixture method (Vrac et al. 2007), Principal component analysis (PCA) coupled with K means cluster analysis (Galambosi et al. 1996; Corte-Real et al. 1999; McKendry et al. 2006), fuzzy rule based clustering technique (Ghosh and Mujumdar 2006; Wetterhall et al. 2009) eigenvector based analysis including principal component analysis (Hewitson and Crane 1992), T-mode Principal component analysis (Huth 1997; 2000) and common empirical orthogonal function (Benestad 2001), have been found in the literature.

With the continuous progress in the development of AOGCMs over the last few decades, it has been noted that AOGCMs should be capable of simulating synoptic scale features and their daily variability (Boer et al. 1992; McFarlane et al. 1992; McKendry et al. 1995). However, only a few studies have examined the ability of AOGCMs in simulating synoptic scale circulation patterns (e.g. Crane and Barry 1988; Hewitson and Crane 1992, McKendry et al. 1995, 2006; Lapp et al. 2002; Schoof and Pryor 2006; Demuzere et al. 2009; Lynch et al. 2006; Cassano et al. 2006, 2007; Finnis et al. 2007, 2009a, 2009b; Anagnostopoulou et al. 2008, 2009).

A number of studies have used MSLP (e.g. Crane and Barry 1988; Hewitson and Crane 1992; Cassano et al. 2006, 2007; Lynch et al. 2006; McKendry et al. 2006; Demuzere et al. 2009; Finnis et al. 2009a, 2009b) and 500 hpa geopotential height fields (e.g. Lapp et al. 2002; Schoof and Pryor 2006; Anagnostopoulou et al. 2008, 2009;) or both (McKendry et al. 1995) to simulate the synoptic scale circulation.

3.2 Assessment of Model Performance at Synoptic Scale

The review in this section focuses mainly on the individual or collective performance of GCMs in reproducing the historical synoptic pattern. In a pioneering study, Crane and Barry (1988) applied automated Kirchhofer map pattern categorization followed by rotated principal component analysis (RPCA) to compare the daily observed MSLP synoptic patterns with the simulated MSLP patterns generated by GISS

(Goddard Institute for Space Studies) GCM over the Arctic. Hewitson and Crane (1992) evaluated the accuracy of representativeness of GISS GCM II at reproducing daily synoptic scale circulation pattern over continental United States using a PCA. McKendry et al. (1995) used the automated Kirchhofer map typing technique to evaluate the ability of Canadian Climate Center (CCC) second generation GCM in simulating regional to synoptic scale circulation by using daily sea level pressure and 500 hPa geopotential height over western north United States. Lapp et al. (2002) employed the first generation of Coupled Global Model (CGCM1) of Canadian Centre for Climate Modelling and Analysis (CCCMA) to analyze the link between regional or local precipitation and synoptic scale circulation pattern over western North America using 500 hpa geopotential height values.

Schoof and Pryor (2006) investigated the ability of two coupled GCMs namely Hadley Center's third generation Coupled Climate Model (HadCM3) and the second generation of Canadian Centre for Climate Modelling and Analysis CGCM (CGCM2) in simulating synoptic scale circulation pattern over Midwest United States and their links with NAO and PNA using 500 hPa geopotential height fields.

Cassano et al. (2006) used 10 CMIP3 AOGCMs to examine the accuracy of model simulation of Arctic synoptic circulation using the neural network classification known as Self Organizing Maps (SOM) to daily SLP data. Cassano et al. (2007) in a sequel paper further investigated the effect of change in synoptic circulation on net precipitation in Arctic by using an ensemble of 15 CMIP3 AOGCMS. In the Antarctic, Lynch et al. (2006) employed the 10 model ensemble used by Cassano et al. (2006) to study the agreement of Antarctic synoptic circulation simulation with NCEP/NCAR reanalysis (NNR) and European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA-40) by applying SOM to daily SLP data for the summer and winter. Finnis et al. (2009a) studied the representativeness of 14 CMIP3 GCMs in assessing the link between synoptic scale circulation pattern and precipitation influencing the hydroclimatology of the Mackenzie River Basin (MRB) in Canada by applying SOM to daily SLP data. In a companion paper, Finnis et al. (2009b) compared the same 14 model ensemble against ERA-40 to investigate the role of synoptic forcing on the Eurasian watersheds by applying SOM to daily SLP data.

Anagnostopoulou et al. (2009) assessed the ability of HadAM3P to reproduce the Lamb synoptic types (Lamb 1972, Yarnal 1993, O'Hare and Sweeney 1993) and precipitation over 3 areas in the Mediterranean namely Greece, Cyprus and central Italy by using daily 500 hPa geopotential height anomalies. In a previous work, Anagnostopoulou et al. (2008) employed HadAM3P to reproduce the Lamb synoptic types over Europe and the Mediterranean. Demuzere et al. (2009) used the Lamb weather type classification based on 6 hourly SLP values averaged over a day to appraise the ability of ECHAM5 in reproducing the circulation pattern and variability over western and central Europe. McKendry et al. (2006) undertook Principal component analysis based classification to compare the daily MSLP synoptic pattern reproduced by CGCM2 with that of observed NNR data over the Pacific Northwest region of North America.

The Results from above studies indicate that in most cases, GCMs reproduce the observed synoptic pattern but the frequency of circulation pattern is often not accurate and simulations are not consistent across seasons. Crane and Barry (1988) found that the simulated spatial and temporal characteristics were broadly similar with the observed data. However, model simulation had more extreme values compared to observed data. Hewitson and Crane (1992) reported better agreement for spatial pattern than for temporal pattern but concluded the results were better than Crane and Barry (1988) because of difference in GCM resolution and selection of study area. McKendry et al. (1995) found that the model simulation successfully reproduced the range of synoptic types but there was significant difference in seasonal frequency and variability of the synoptic types in the sense that the 3 most common MSL synoptic types showed significantly different mean annual frequency in all 4 seasons.

Lapp et al. (2002) stated that the model simulation reasonably reproduced the 500 hPa synoptic types but there was a significant difference between modeled and observed frequency distribution for one synoptic type. Schoof and Pryor (2006) found good agreement between GCM simulation and reanalysis data in reproducing the range of synoptic types but also reported significant model differences. HadCM3 overpredicted the dominant map pattern 1 (map type 1) and underpredicted the second and third most recurring map pattern (map type 8 and 11 respectively). Frequency of synoptic types produced by CGCM2 showed better agreement with the observed map pattern classification but the map type 1 was under produced which was contrary to HadCM3 simulations. This was attributed to overrepresentation of meridional flow in HadCM3. Schoof and Pryor (2009) discussed some of the causal links between positive and negative phases of NAO and PNA that can influence the frequency of synoptic types and recommended an evaluation of synoptic scale circulation by a larger suite of AOGCMs across various spatial and temporal scales.

Cassano et al. (2006), Cassano et al. (2007), Lynch et al. (2006), Finnis et al. (2009a, 2009b) found a varying degree of model efficiency when SOM was applied to model ensemble. Cassano et al. (2006) found that in winter, model ensemble produced a synoptic pattern that was close to the observed synoptic pattern but the frequency of some of the synoptic type was different from the observed data. Only 3 among 10 models were able to match the observed synoptic pattern individually. In summer, model ensemble failed to reproduce the observed pattern but 5 among the 10 models were able to simulate the observed pattern to some extent individually.

Cassano et al. (2007) identified a subset of 4 models, which was able to simulate the basic Arctic synoptic circulation pattern when compared with reanalysis, to assess the change in precipitation over the 21st century. Lynch et al. (2006) discovered that the performance of model ensemble was satisfactory in the summer and winter but some models performed very poorly in representing the synoptic circulation over Antarctic. Finnis et al. (2009a) found significant variation among models but circulation patterns were better reproduced during the summer and winter compared to the autumn and spring. Finnis et al. (2009b) also found that the results varied among models and across seasons with best results being produced in the summer and winter.

It was noted that third generation of Community Climate System Model (CCSM3) of NCAR (National Center for Atmospheric Research) that was used by Cassano et al. (2006, 2007) and Finnis et al. (2007, 2009a, 2009b) showed varying degree of efficiency. Cassano et al. (2007) found that CCSM3 was one of the best performing models over Arctic and identified CCSM3 as one of the 4-model subset ensemble to simulate future precipitation trend. CCSM3 performance was reasonably good over the

Arctic and particularly in the summer as was found by Cassano et al. (2006). The study of Finnis et al. (2009a) revealed that CCSM3 was the poorest performing model in the MRB but it was concluded that individual model performance can vary across different regions taking into account that CCMS3 performed well in Cassano et al. (2006, 2007) and Finnis et al. (2007). Sheridan and Lee (2010) stated that while assessing the representation of precipitation by the GCMs relative to synoptic scale circulation pattern, it has to be taken into account that GCMs are not particularly good at simulating precipitation at local scale. Finnis et al. (2009a; 2009b) and Sheridan and Lee (2010) attributed the model errors to difficulty in GCM simulation of the processes related with precipitation.

Among the studies that used Lamb synoptic classification, Anagnostopoulou et al. (2008) found that the most prominent anticyclonic type was overestimated in the spring and summer and underestimated in the autumn and winter. The most prominent cyclonic type was underestimated in the summer and winter and overestimated in the spring and autumn. 2 cyclonic types were overestimated and 2 other cyclonic types were underestimated across all the seasons. During the winter, 3 anticyclonic types were overestimated among which one was statistically significant. Positive and negative significant differences were found for the other cyclonic types across 3 other seasons. Anagnostopoulou et al. (2009) found that the model simulated the mean circulation patterns well but the anticyclonic types were overproduced while cyclonic types were underproduced during the summer and winter. Demuzere et al. (2009) found better model performance in reproducing the synoptic types during the winter.

McKendry et al. (2006) found that the model successfully reproduced the range of surface synoptic types but the frequency of synoptic types were not accurately simulated which is consistent with the findings of McKendry et al. (1995) and Schoof and Pryor (2006). The model overestimated the frequency of 3 warm, wet types and underestimated the frequency of 3 cold types. Best model performance was achieved during the summer, when the synoptic circulation is more stable. Demuzere et al. (2009) concluded that consistent circulation pattern simulation across all seasons is required for the application of GCMs in downscaling, the assessment of climate change and other applications. Spatial and temporal correspondence between observed and simulated synoptic scale circulation pattern will be a key area to determine the ability of the state of the art AOGCMs across scales.

Yin (2005) analyzed 15 coupled CMIP3 GCMs for 21st century climate simulations and reported a consistent poleward shift of the storm tracks is more augmented in Southern Hemisphere compared to Northern Hemisphere. Poleward shift of storm tracks is accompanied by the poleward shift of the surface wind stress and precipitation causing an increased occurrence of the higher index state of Northern Annular Mode and Southern Annular Mode. Chang et al. (2012) applied 23 CMIP5 and 11 CMIP3 models to simulate changes in the storm track for the 21st century and found a stronger trend in the poleward shift of the storm tracks in the Southern Hemisphere and also to some extent in the Northern Hemisphere. The CMIP5 models projected a significant increase in the frequency of extreme cyclones during the Southern Hemispheric winter which is consistent with the CMIP3 projections. However, CMIP5 models projected a larger significant decrease, compared to CMIP3 models, in the frequency of extreme cyclones for the Northern Hemispheric winter. Zappa et al. (2013) reported the improvement in CMIP5 models over CMIP3 simulations in reproducing the frequency and intensity of North Atlantic Cyclones but systematic biases affecting the position of the storm track leading to overestimation of the frequency and intensity of the storms in central Europe and underestimation of frequency and intensity of storms over the Norwegian sea in winter was reported. In summer the position of the storm track was captured well but the number of cyclones were underestimated. Cattiaux et al. (2013) found that CMIP5 models reproduce a stronger than observed North Atlantic jet stream. Nishii et al. (2015) reported some improvement in reproducing the storm-track activity over Arctic by CMIP5 models when 17 CMIP5 model simulations were compared with 17 CMIP3 model simulations but found consistent bias in the form of underestimation of summertime storm-track activity in CMIP3 and CMIP5 models.

3.3 Summary

Aforementioned studies examined the ability of a single model, (e.g. Crane and Barry 1988; Hewitson and Crane 1992; McKendry et al. 1995, 2006; Lapp et al. 2002; Demuzere et al. 2009, Anagnostopoulou et al. 2008, 2009) or two models, (e.g. Schoof and Pryor 2006). The importance of need for inclusion of larger suite of models to better understand the links between teleconnection scale indices and synoptic scale condition is emphasized by Schoof and Pryor (2009). Sheridan and Lee (2010) highlighted the need for the application of multiple models to address the uncertainty inherent in a single model simulation. Multimodel ensemble have been employed in studies that applied SOM (e.g. Cassano et al. 2006, 2007; Lynch et al. 2006; Finnis et al 2009a, 2009b) and in more recent series of papers that made a comparative analysis between CMIP3 and CMIP5 (e.g. Chang et al. 2012; Nishii et al. 2015) or evaluated individual CMIP3 (e.g. Yin 2005) or CMIP5 model performance (e.g. Zappa et al. 2013, Cattiaux et al. 2013). In general, the simulation of observed synoptic patterns are captured by the GCMs but the frequency of the synoptic types are often different and not consistent across seasons. The intermodal (e.g. Yin 2005, Cassano et al. 2006, 2007; Lynch et al. 2006; Schoof and Pryor 2006, Finnis et al 2009a, 2009b, Zappa et al. 2013, Nishii et al. 2015) and intra model (e.g. Cassano et al 2006, 2007; Finnis et al 2007, 2009a) differences reported in the body of work discussed in this section indicates the need of additional research to perform an evaluation of large suite of contemporary climate models across various spatial and temporal scales as the agreement between observed and simulated synoptic scale features represent an important model diagnostic. The ability of the models to capture the synoptic scale variations due to changes in the large scale modes of variability across a range of time scales is an important aspect of model evaluation as the regional scale climate simulation is governed by changes in synoptic scale features. Table-2 provides a summary of major findings of model performance at synoptic scale.

Table-2: A Summary of Model Performance at Synoptic Scale

Primary reference	Dataset(s)	Model(s) used	Data type	Major findings
Cassano et al. (2006)	European Center for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) and NCEP/NCAR reanalysis (NNR) for observed temperature, precipitation and sea level pressure (SLP) data	10 CMIP3 models	Daily	In winter, model ensemble simulated the observed synoptic pattern but frequency of synoptic types was different than observed. In summer model ensemble failed to reproduce the observed synoptic pattern and only 5 models were able to match the observed synoptic pattern to some extent individually.
Cassano et al. (2007)	ERA-40 and NCEP/NCAR reanalysis for observed precipitation and SLP data.	15 CMIP3 models	Daily	Intermodel differences in reproducing the observed synoptic climate over Arctic is reported and a subset of 4 best performing models is selected to simulate changes in net precipitation over Arctic in future.
Lynch et al. (2006)	ERA-40 and NCEP/NCAR reanalysis for observed temperature, precipitation and SLP.	10 CMIP3 models	Daily	Model ensemble reasonably reproduced the Antarctic Circulation but some models showed poor performance in simulating the circulation pattern.
McKendry et al. (2006)	NCEP/NCAR reanalysis (NNR) for observed sea level pressure data.	A single CMIP2 GCM	Daily	Model successfully reproduced the observed synoptic pattern but the frequency of synoptic types was not accurately simulated.
Schoof and Pryor (2006)	NNR for observed sea level pressure and geopotential height data.	2 CMIP2 GCMs	Daily	In general the models showed good agreement with the observed synoptic pattern. However, model differences are noted in reproducing the frequency of synoptic types.
Finnis et al. (2009a)	ERA-40 for observed precipitation and SLP.	14 CMIP3 models	Daily	Compared to observed circulation pattern, model performance varies significantly across models and seasons with best match being produced in summer and winter.
Finnis et al. (2009b)	ERA-40 for observed precipitation and SLP.	14 CMIP3 models	Daily	Models show the best correspondence with observed synoptic pattern during summer and winter. A subset of 5 best performing models is selected for future projections.

Table-2: Continued

Primary reference	Dataset(s)	Model(s) used	Data type	Major findings
Finnis et al. (2009b)	ERA-40 for observed precipitation and SLP.	14 CMIP3 models	Daily	Models show the best correspondence with observed synoptic pattern during summer and winter. A subset of 5 best performing models is selected for future projections.
Chang et al. (2012)	ERA-Interim data for observed meridional wind and SLP.	11 CMIP3 and 23 CMIP5 models	6-hourly	CMIP5 models project a significant increase in the frequency of extreme cyclones during Southern Hemispheric winter which is consistent with CMIP3 projections. However, compared to CMIP3 projections, CMIP5 models show a larger significant decrease in the frequency of extreme cyclones during Northern Hemispheric winter.
Cattiaux et al. (2013)	E-OBS v3.0 for observed European temperature and NCEP/DOE reanalysis for observed geopotential height data	33 CMIP5 models	Daily	CMIP2 and CMIP3 models suggested an increase in the positive phase of NAO in the future influencing the European temperature trend. However, CMIP5 models projected an increase in the negative phase of NAO in winter. CMIP5 models reproduce a stronger than observed North Atlantic jet stream.
Zappa et al. (2013)	ERA-Interim, the Japanese 25 year Reanalysis (JRA-25), NCEP Climate Forecast System Reanalysis (NCEP CFSR) and NASA Modern Era Retrospective-Analysis for Research and Applications (NASA MERRA) for observed zonal and meridional wind speed and mean sea level pressure.	22 CMIP5 models and 19 CMIP3 models	6-hourly	Reported improvement in the representation of number and intensity of Northern Hemispheric extratropical storm tracks in CMIP5 models over CMIP3 simulations. CMIP5 models are better at reproducing the location and tilt of North Atlantic storm track in summer. However, CMIP5 models underestimate the intensity of cyclones in both summer and winter and systematic bias affected the spatial distribution of storm tracks.

Table-2: Continued

Primary reference	Dataset(s)	Model(s) used	Data type	Major findings
Nishii et al. (2015)	ERA-Interim, JRA-25, NNR, ERA-40, NCEP CFSR and JRA-55 for observed temperature, SLP and meridional wind.	17 CMIP3 and 17 CMIP5 models	Daily	CMIP5 models show improvement in reproducing the summertime storm track activity over Arctic. However, systematic bias was found in both CMIP3 and CMIP5 models. 10 out of 17 CMIP3 models predict an increase in the total number of cyclones but 14 out of 17 CMIP5 models show a decrease in future. Recommendation of more reliable simulation of summertime NAM variability and how that influences the present and future land temperatures over Eurasia is made.

4. Model Simulation of Regional Scale Features

4.1 Introduction

Comparison of AOGCM simulations with observed data at the grid point scale has led to the notion that AOGCMs do not show agreement even when simulating the same variable using the same scenario over the same region (Kundzewicz et al. 2007). Global climate is the response of the climate system to the large scale processes (differential solar heating, rotation of earth and surface features that includes distribution of land, ocean and mountains) but regional climate is the response of global climate to regional details (Zorita and von Storch 1999). At the smallest spatial scale model errors will always be large even if the AOGCMs agree well on a large scale (Grotch and MacCracken 1991, Masson and Knutti 2011). AOGCMs are unable to provide locally relevant climate data for regional applications and downscaling is a method that is used by climate scientists to generate climate information on a smaller spatial scale from AOGCMs.

When we try to understand climate system behavior or impact of climate change in a particular region, downscaling (statistical or dynamic or hybrid) approach is applied to the AOGCM output. Statistical downscaling establishes a relationship between predictor (large scale atmospheric variable) and predictand (local regional or small scale variable). Various downscaling methodologies (see Wilby and Wigley 1997) are used to bridge the gap between what AOGCMs are able to provide and what these finer scale applications will require (Lim et al. 2007).

Downscaling produces the regional climate information but results in adding another layer of complexity that stems from a host of uncertainties associated with the regionalization process (see Giorgi and Francisco 2000, Hawkins and Sutton 2009, Schoof 2013). Most of the downscaling techniques do not have the provision of the parent AOGCM deriving the feedback from regional processes (Schoof 2013). One of the primary conditions that needs to be fulfilled for a successful statistical downscaling approach is that predictor variable should be well simulated by GCM (Busuioc et al. 2001, Wilby et al. 2004, Benestad et al. 2008, Schoof 2013). If the model simulation of large scale and synoptic scale features are not credibly replicated by the GCM at the timescale required for the regional impact assessment, the downscaled climate information is also likely to lack fidelity (Schoof and Pryor 2006).

Uncertainty, that results from choice of AOGCMs or using different AOGCMs, increases as we approach finer scale and adds to the uncertainty associated with the downscaling technique and this could be addressed by determining the scale at which optimal simulation of large scale predictor variables is achieved which can greatly enhance the value of statistical downscaling to decision makers (Schoof 2013). An optimal scale exists between the continental scale, where AOGCMs are most effective (model errors are less) but regional signal is not retained, and the regional scale where most of the surface features are captured but model errors are higher (Masson and Knutti 2011).

4.2 Assessment of model performance at regional scale

Uncertainty in the AOGCM simulation increases as we move from a global scale to a regional scale (Zorita and von Storch 1999, Williamson and Laprise 2000, Räisänen 2001, Randall et al. 2007). In order to circumvent this problem, climate scientists have used the broad subcontinental scale, considering it skillful for regional impact studies (e.g. Christensen et al. 2007; Giorgi and Francisco 2000; Ruosteenoja et al. 2003). Following the work of Grotch and MacCracken (1991), there have been various interpretations of “skillful scale” (e.g. von Storch et al. 1993; Zorita and von Storch 1999).

The focus of this section is on the assessment of model skills on regional scale with the need for identification of optimal scale for variables other than temperature and precipitation in contemporary climate models. For a regional impact study it is important to capture most of the features regulating climate in that particular region and coarse resolution AOGCM output at grid point level is not very effective in this regard. The AOGCMs are more efficient at larger continental scale but may fail to simulate the regional circulation pattern that leads to extreme precipitation events (Christensen and Christensen 2003). This calls for finer scale simulation (Kundzewicz et al. 2007, Schoof et al. 2009, Maruan et al. 2010) and downscaling is required to make the AOGCM simulations relevant for a sub grid level study.

Portman et al. (1992) aptly visualized that the importance of AOGCM application for studying the impact of climate change at regional scale will increase in near future. In order to bridge the gap between inability of AOGCMs to provide reliable information at local scale and need for information at small scale for sub grid level studies, an assessment of performance of AOGCMs across a range of spatial and temporal scales is required. Chervin (1981) and Portman et al. (1992) used standard statistical analysis to evaluate this scale for precipitation and temperature respectively. This approach has been applied in several downscaling studies (e.g. Schoof et al. 2007). Masson and Knutti (2011) and Räisänen and Ylhäisi (2011) recently identified an “optimal smoothing scale” for temperature and precipitation using CMIP3 models. However, only temperature and precipitation were analyzed. There remains a need for detailed analysis of other widely used downscaling variables to present a comprehensive account of ability of CMIP5 AOGCMs across scales.

Grotch and MacCracken (1991) assessed climate sensitivity of GCMs across various spatial scales and was seminal in introducing the concept of skillful scale (Benestad et al. 2008). They found that even though models agree well on a large scale but at a regional scale or grid point level, “very large regional or pointwise differences can, and do exist” and for temperature this pointwise difference can be more than 20K (Grotch and MacCracken 1991, Benestad et al. 2008). They also found that model disagreement becomes more pronounced at smaller scales. Grotch and MacCracken (1991) opined that there is a need for comprehensive regional and seasonal evaluation of GCMs to make it more useful or meaningful for regional or finer scale studies. Following the work of Grotch and MacCracken (1991), von Storch et al. (1993) defined the minimum scale as the grid point distance between two adjacent grid points and skillful scale was defined as a scale consisting of more than or equal to 8 grid points or the distance between 8 or more adjacent grid points. Regional scales and large scales were defined as scales smaller and larger than the skillful scales respectively. After Grotch and MacCracken (1991), Zorita and von Storch (1999) stated that GCMs are to be considered less skillful as the spatial scale approaches a distance between few grid points. Huth and Kyselý (2000) also stated that the GCMs are more accurate in the simulation of large scale fields compared to simulation at a single grid point.

The AOGCMs of the present generation mostly have a grid size of approximately 100-400 km (Wilby et al. 2009, Endo et al. 2012). Christensen et al. (2007) in the 4th Assessment Report of the IPCC mentions the gridbox resolution of state of the art AOGCMs to be roughly about 200 km and that scales below the computational grid size should be considered unreliable. For CMIP3 models, this is equivalent to the minimum scale defined by von Storch et al. (1993). A lack of reliability of model simulations at the minimum scale or regional scale has prompted climate scientists to opt for larger sub continental scales for regional impact assessment (Masson and Knutti 2011). Christensen et al. (2007) considered 1000 km X 1000 km or 10^6 km^2 as the horizontal length scale at which AOGCM simulations would be considered useful for regional climate analysis. Giorgi and Francisco (2000) used 10^7 km^2 as the upper limit of the regional scale at which regionally averaged climate information would still be relevant for regional applications. Ruosteenoja et al. (2003) opined that most meaningful information for regional climate analysis could be obtained at the sub continental scale of 10^6-10^8 km^2 and used this scale for regional climate study.

In order to identify the desired scale of model performance for regional impact assessment, it is required to determine the optimum number of grid points at which model errors will be relatively less but most of the spatial features will still be captured effectively. A few pioneering studies have attempted model evaluation across scales, but using only precipitation (e.g. Chervin 1981), temperature (e.g. Portman et al. 1992), temperature and precipitation (Grotch and MacCracken 1991; Masson and Knutti 2011; Räisänen and Ylhäisi 2011), near-surface temperature, precipitation and sea level pressure (Bhend and Whetton 2013). Masson and Knutti (2011) identified the desired scale of model performance by comparing the observed mean and variance with that of AOGCM simulated mean and variances over different spatial aggregation and time periods. Räisänen and Ylhäisi (2011) and Masson and Knutti (2011) evaluated CMIP3 model performances. Bhend and Whetton (2013) provided a comparative analysis between CMIP3 and CMIP5 model performance using multimodel ensemble average. There is paucity of literature aimed at evaluating optimal smoothing scale for other important variables (surface air temperature, sea level pressure, eastward wind, northward wind, geopotential height and specific humidity) which are widely used in downscaling studies.

4.3 Summary

AOGCMs are relatively more skillful in simulating average climate at continental scales across seasons but they are not as reliable while approaching smaller spatial and temporal scales (Grotch and MacCracken 1991). Policy makers, planners, engineers and impact modelers need information at finer spatial and temporal scale than AOGCMs are currently able to provide (Schoof et al. 2009, Maruan et al. 2010).

Use of AOGCMs to investigate climate change impacts assumes that they adequately simulate climate across a range of spatial and temporal scales. While the shortcomings of AOGCMs at the scale of an individual grid point have been recognized within the AOGCM downscaling community, there has been paucity of literature that identifies the scale at which AOGCMs perform well, especially for variables other than temperature, and for large model ensembles. To what extent AOGCMs would be able to provide reliable information for regional impact analysis would be best answered by evaluation of AOGCMs at the scale at which AOGCM simulation would provide better agreement with the observed statistical moments at regional scale. In order to identify the desired scale of model performance for regional impact assessment, it is required to determine the optimum number of grid points at which model errors will be relatively less but most of the spatial features will still be captured effectively. Optimal smoothing scale for temperature and precipitation has been identified for temperature and precipitation (e.g. Masson and Knutti 2011, Räisänen and Ylhäisi 2011) and near-surface temperature, precipitation and sea level pressure (Bhend and Whetton 2013) but there have been no attempts to identify optimal smoothing scale for widely used downscaling predictors. The extension of the aforementioned works by evaluating AOGCM skills across various spatial, temporal scales, large scale atmospheric variables among latest generation of CMIP5 climate models while also assessing the ability of individual models is highly recommended. Table-3 provides a summary of major findings of model performance at regional scale.

Table-3: A Summary of Model Performance at Regional Scale

Primary reference	Dataset(s)	Model(s) used	Data type	Major findings
Grotch and MacCracken (1991)	Oort Historical temperature data, Jaeger and Schutz-Gates historical precipitation data.	4 uncoupled GCMs	Seasonal (winter and summer)	Models agree well on a large scale but at a regional scale or grid point level, model disagreement becomes more pronounced. This pointwise difference can be more than 20K for temperature. Comprehensive regional and seasonal evaluation of GCMs was recommended for finer scale applications of GCMs.
von Storch et al. (1993)	29 stations from World Meteorological Station Climatology (WMSC) datasets for temperature and precipitation and Comprehensive Ocean Atmosphere Data Set (COADS) for SLP.	A coupled AOGCM	Annual cycle	Reliability of model simulation is dependent on the spatial scale. Skillful scale is defined as the scale consisting of more than or equal to 4-8 grid points.
Giorgi and Francisco (2000)	Observed datasets of the Climatic Research Unit of the University of East Angalia for Temperature and Precipitation.	5 coupled AOGCMs	Seasonal (winter and summer)	Inter-model variability is found to be the major source of uncertainty that dominated over inter-scenario and internal model variability for regional impact assessment. 10^7 km^2 is considered as the upper limit for regional scale aggregation of AOGCMs.
Ruosteenoja et al. (2003)	Observed datasets of the Climatic Research Unit of the University of East Angalia for Temperature and Precipitation.	7 coupled CMIP2 AOGCMs	Seasonal (all 4) and annual cycle	Considered the sub continental scale of 10^6-10^8 km^2 to be most useful for regional impact analysis.
Christensen et al. (2007)	N/A	N/A	N/A	Considered 1000 km X 1000 km or 10^6 km^2 as the scale that could be used for regional climate analysis.

Table-3: Continued

Primary reference	Dataset(s)	Model(s) used	Data type	Major findings
Masson and Knutti (2011)	European Center for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) for observed temperature, Climate Prediction Center (CPC) Merged Analysis for Precipitation (CMAP) and Global Precipitation Climatology Project (GPCP) for observed precipitation.	24 CMIP3 AOGCMs	Monthly	Identified the optimal smoothing scale for temperature and precipitation. A penalty function that combines model error and spatial information lost from aggregation is minimized to determine the optimum number of grid points at which model errors will be relatively less but most of the spatial features would still be captured effectively. An optimal smoothing scale of 2000 Km was proposed for CMIP3 models subject to variable, study area and smoothing technique used.
Räisänen and Ylhäisi (2011)	ERA-40 and NCEP/NCAR reanalysis (NNR) for observed temperature, CMAP and GPCP for observed precipitation	24 CMIP3 AOGCMs	Monthly	The Optimal smoothing scale of 2000 Km for CMIP models proposed by Masson and Knutti (2011), to obtain information about local climate, is reported to be higher for individual model and more so for multimodal means. For temperature, the scale is stated to be 126 Km and 1008 Km for multimodel mean and individual models respectively. For precipitation, the optimal smoothing scale is 200 Km and 1600 Km for multimodel mean and individual models.
Bhend and Whetton (2013)	GISS surface temperature analysis (GISTEMP) for observed temperature, HadSLP2 dataset for observed sea level pressure and Global Precipitation Climatology Center's (GPCC) Variability Analysis of Surface Climate Observations (VASClimO) version 1.1 for observed precipitation.	24 CMIP3 and 26 CMIP5 models	Seasonal (winter and summer)	No sign of improvement is reported in the ability of CMIP5 models over their CMIP3 counterparts in reproducing locally relevant temperature, precipitation and sea level pressure data. Inconstancies between observed and simulated changes in temperature and sea level pressure is significant while simulated changes in precipitation is not significantly different from observed changes.

5. Synthesis

An evaluation of AOGCMs at large scale, where the models are generally considered robust, has been reviewed in section 2. This has been attempted by evaluating and comparing CMIP5, CMIP3 and previous intercomparisons and how well do they correspond with the observed spatial and temporal pattern of the major modes of variability. A general improvement has been noted among the CMIP5 models compared to the performance of CMIP3 models. In general, models mostly represent a recognizable spatial and temporal pattern consistent with the observed spatial and temporal pattern of the modes of climatic variability. Common errors in reproducing the strength of center of actions and too regular variability in time series compared to observations have been noted. Models tend to simulate different modes of variability with varying degree of skills. Models that simulate poor (best) temporal variability are found to reproduce the best (poor) spatial pattern which emphasizes the importance of including all the models in analyzing the spatial and temporal correspondence. ENSO simulations continue to need improvement in reproducing the observed amplitude, period, irregularity and skewness. Model skill varies depending on the mode of climate variability studied, spatial and temporal characteristics, study area and model used.

This is followed by model evaluation at synoptic scale, which is the intermediate scale between large scale and regional scale, in section 3. A detailed evaluation of the state of the art AOGCMs is attempted to examine how the AOGCMs perform in simulating the synoptic scale patterns. This has been achieved by examining the ability of AOGCMs in capturing the observed spatial and temporal variability of synoptic scale features. In general, the simulations of observed synoptic patterns are reproduced by the GCMs but the frequencies of the synoptic types vary and remain inconsistent across seasons. Differences in model performances could be associated with the links between large scale modes of climate variability and synoptic scale condition, study area and model selection. In section 4, evaluation of model performance at the smallest regional scale is presented to further analyze model reliability at a range of scales. This has been achieved by reviewing the shortcomings of GCMs at shorter spatial and temporal scales and how this can be improved by analyzing model performance across a range of spatial and temporal scales to identify the optimal scale at which the model simulations for regional analysis would show best correspondence with the observed statistical moments. This emphasizes the need to determine a desired scale of model performance for the latest suite of climate models and how this scale varies among variables, models, spatial and temporal scales. It is critical to understand synoptic scale climate in the context of large scale climate. Links between large scale modes of climate variability and synoptic scale climate has been analyzed by Schoof and Pryor (2006). Regional scale climate is influenced by synoptic scale features which are governed by modes of variability occurring at large scale. Grotjahn et al. (2015) analyzed extreme temperature events at regional scale in the context of large scale meteorological patterns (LSMP). How well a model will perform at the regional scale is dependent on model simulation of local processes and also on the reliability of model performance at synoptic scale and large scale.

6. Significance

Model performance across large scale, synoptic scale and regional scale has been reviewed to provide an overview of strength and weaknesses of contemporary climate models. The reliability of simulation of modes of climate variability at the large scale improves our confidence in the model's ability to reproduce the governing features of the climate at hemispheric scale. Varying degree of the skills shown by the individual CMIP3 and CMIP5 models in reproducing the observed spatial and temporal pattern highlights the need of employing a large suite of contemporary climate models to examine their individual and collective skills in reproducing the spatial and temporal patterns of modes of climate variability. Credible simulation of synoptic scale features increases our confidence in model's ability to simulate the regional features more effectively. Intermodel and intramodel differences among contemporary climate models in reproducing the synoptic scale climate emphasize the importance of analyzing the model simulation at synoptic scale to determine model efficiency at large scale and regional scale. Further research is required to evaluate the contemporary climate models across a range of spatial and temporal scales to reduce the uncertainty associated with the application of the models to regional impact studies, which will greatly help the downscaling community to assess the scale at which statistical downscaling predictors are adequately reproduced by AOGCMs. This can greatly benefit the Impact modelers, planners and engineers, who would require climate information at smaller regional scale.

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APPENDICES

Appendix A – CORRESPONDENCE

Correspondence related to Figure 1

From: Stoner, Anne <anne.stoner@ttu.edu>
Sent: Tuesday, April 14, 2015 11:01 AM
To: Saurav Chakraborty
Subject: Re: request for permission to use the figure from Stoner et al. 2009

Hi Saurav,

Go ahead and use the figure! I'm glad it relates to your research, and it sounds like an interesting study.

Best of luck with your paper and your MS.
Anne

On Apr 14, 2015, at 10:54 AM, Saurav Chakraborty <saurav@siu.edu> wrote:

Dear Dr. Stoner,

I am pursuing MS in Geography and Environmental Resources at Southern Illinois University in Carbondale. I am working on a research paper for which I am looking at the performance of contemporary climate models across various spatial and temporal scales. I am chiefly trying to examine AO, NAO, PNA, ENSO, AMO and PDO. I have read your paper entitled "Assessing General Circulation Model Simulations of Atmospheric Teleconnection Patterns" for this purpose many times. I wanted to include the figure 1 of Stoner et al. (2009) for the visual representation of observed spatial patterns of 6 teleconnections in my research paper. The graduate school requires me to have a written permission from you to use this figure in my paper. I will be grateful if you please allow me to cite this figure in my paper.

With best regards,

sincerely,

Saurav

Appendix A – CORRESPONDENCE

From: Nathans, Jinny <jnathans@ametsoc.org>
Sent: Thursday, October 8, 2015 8:05 AM
To: Saurav Chakraborty
Subject: Re: Permission to use a figure for my Master's Research Paper

Dear Saurav—

My name is Jinny Nathans and I'm the Permissions Officer at AMS. Your question was referred to me. This signed message constitutes permission to use the material requested in your email below.

You may use the figure in your paper with the following conditions:

+ please include the complete bibliographic citation of the original source, and
+ please include the following statement with that citation: ©American Meteorological Society. Used with permission.

Thanks very much for your request and if you need any further information, please get in touch with me. My contact information is below.

Regards,

Jinny Nathans
Permissions Officer
American Meteorological Society

jnathans@ametsoc.org
617 226-3905

On Tue, Oct 6, 2015 at 7:18 PM, Saurav Chakraborty <saurav@siu.edu> wrote:
Hi,

My name is Saurav Chakraborty and I am a Master's student in the Dept. of Geography and Environmental Resources in The Southern Illinois University of Carbondale

Appendix A – CORRESPONDENCE

I would like to use a figure from "Anne Marie K. Stoner, Katharine Hayhoe, and Donald J. Wuebbles, 2009: Assessing General Circulation Model Simulations of Atmospheric Teleconnection Patterns. *J. Climate*, **22**, 4348–4372. doi: http://dx.doi.org/10.1175/2009JCLI2577.1"

The figure I would like to use is figure. 1 from the above mentioned article.

This figure would be included in the literature review of my Master's Research paper and I have the permission of the author (Anne Marie K. Stoner). However, the graduate school told me that permission would be required from the Journal as well. I do not know exactly whom I should write to in AMS regarding this, so could you please help me with this?

AMS Journals Online - Assessing General Circulation Model Simulations of Atmospheric Teleconnection Patterns
Anne Marie K. Stoner, Katharine Hayhoe, and Donald J. Wuebbles, 2009: Assessing General Circulation Model Simulations of Atmospheric Teleconnection Patterns. J. Climate, 22, 4348–4372. doi: http://dx.doi.org/10.1175/2009JCLI2577.1
Read more...

Thanks and regards

Sincerely,

Saurav Chakraborty
Graduate Student
Dept. of Geography and Environmental Resources
1000 Faner Dr.
Southern Illinois University Carbondale
Carbondale, IL-62901

VITA

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Major Professor: Dr. Justin Schoof, Professor and Chair, Dept. of Geography, SIUC